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Numerical Results on Operating Parameters Influence for a Heat Recovery Adsorption Machine

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Abstract

In this paper, a detailed thermodynamic and parametric analysis of simple and regenerative cycle of an adsorptive machine using the activated carbon AC-35/methanol as adsorbent/adsorbate pair is given, where the Dubinin-Astakhov equation is used to describe the isotherm of adsorption.
For describing the thermodynamic cycle, for different operating conditions (evaporation and condensation temperatures), two limit- points concerning the adsorption and the desorption are determined. Two functions of the incoming and outgoing energy for the regenerative cycle using two isothermal adsorbers have been calculated, in order to obtain the heated adsorber temperature at the end of heat recovery. Results are presented in terms of performances. These results demonstrated that the performance coefficient of double bed adsorption refrigeration cycle increases with respect to the single bed configuration.
Several main factors affecting the performance of cycle, the heat recovery ratio, the regenerative heat and the temperature at the end of heat recovery are discussed according to the results of computer simulations.

Keywords: Adsorption system, heat regenerative, thermal performance coefficient, thermodynamic analysis and Simulation.

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Nomenclature

Cp_a	specific heat of the adsorbent, KJ/kg k
Cp_g	specific heat of the adsorber, KJ/kg k
Cp_{ml}	specific heat of the adsorbate in liquid state, KJ/kg k
Cp_{mg}	specific heat of the adsorbate in vapour state, KJ/kg k
COP_s	performance coefficient in the case of one adsorber.
COP_d	performance coefficient in the case of two adsorbers.
D, n	characteristic parameters of adsorbent/adsorbate pair
L	latent heat of evaporation, KJ/kg
m	adsorbed mass, kg/kg
m_a	mass of the adsorbent, kg
m_g	metallic mass of the adsorber, kg
$m_{\max}$	adsorption mass at adsorbed state, kg/kg
$m_{\min}$	adsorption mass at desorbed state, kg/kg
P_e	evaporation pressure, Pa
P_c	condensation pressure, Pa
$P_s(T)$	saturation pressure of the adsorbate, Pa
Q_{ab}	heat that must be supplied to the adsorber for its isosteric heating phase, KJ/kg
Q_{bc}	heat that must be supplied to the adsorber during the desorption phase, KJ/kg
Q_{cd}	heat released during the isosteric cooling phase , KJ/kg
Q_{da}	heat released during the adsorption phase, KJ/kg
Q_c	total heat necessary for heating the adsorber, KJ/kg
Q_{des}	heat of desorption, KJ/kg
Q_f	cooling power, KJ/kg
Q_r	heat recovered, KJ/kg
q_{st}	isosteric heat of adsorption, KJ/kg
R	universal gas constant, J/kg k
r	heat recovery ratio
T	temperature, °C
T_a	adsorption temperature, °C
T_c	condensation temperature, °C
T_{c1}	limit temperature of desorption, °C
T_{c2}	limit temperature of adsorption, °C
T_e	evaporation temperature, °C
T_g	regenerating temperature, °C

Greek letters

w_0	maximum adsorption capacity, m^3/kg
α	coefficient of thermal expansion of the liquid adsorbate

$\rho_l(T)$	density of the adsorbate in liquid state, kg/m^3
ΔT_r	two adsorber temperature difference at the end of heat recovery, °C

1. Introduction

Due to increasing concerns with the environmental problems caused by CFCs and the huge energy consumed by conventional refrigeration systems, sorption refrigeration systems driven by low temperature heat sources have been developed as an economic and environmental friendly alternative. Absorption and adsorption cycles are the two types of sorption refrigeration systems. In all these systems, the mechanical energy consumption is kept to a minimum or null and they can operate with low-grade heat from different sources such as waste heat or solar energy. Absorption cooling systems such as those using LiBr-H2O or H2O-NH3 pairs present many advantages for specific applications. They give better system efficiency than adsorption cooling systems. However, these systems also possess many limitations in operating conditions [1]. The great advantage of adsorption systems over absorption ones is that they can operate without moving parts, having then lower costs of maintenance. Other advantages in comparison with the compression systems are: simple construction, environmentally benign and noiseless. A lot of applications for sorption cooling systems have been viewed in both developed and developing countries such as: storage and conservation of vaccines and medical products, food conservation, refrigeration, air conditioning, chillers and ice production.

A big obstacle to the development of adsorption cycle technology is its low thermal performance. Research efforts by various investigators have therefore been focused on improving the performance of the adsorption cooling system [2]. Where, the modelling of the basic cycle of such systems was the subject of many studies so much theoretical that experimental [3-14], but the theoretical methods remain the best choice, because they can simulate the influence of different parameters on the system's thermal performance, in order to optimize their working before to carry out experiences. The difference among the main developed models in the literature generally lies in the simplifying assumptions, numerical resolution methods, design and use of modeled system.

In the basic cycle of adsorption refrigerating machines, the production of cold is intermittent. To attain higher efficiencies with a continuous production of cold, it is necessary to use advanced cycles. Several kinds of advanced cycles have been proposed and tested. Two main technologies have been developed: regenerative processes with uniform temperature adsorbers and regenerative processes with temperature fronts. In this paper, we interest to the uniform temperature adsorbers. A numerical analysis was carried out, studying the influence of the main parameters on both of regeneration and performance coefficients of the machine and the temperature at the end of heat recovery. A detailed thermodynamic and parametric analysis of a double adsorptive cycle is given, taking into account all thermal contributions occurring in the cycle. The basic fundamentals of the adsorption process are discussed, where the Dubinin-Astakhov equation is used to describe the isotherm of adsorption of the pair activated carbon AC-35/methanol.

2. System description

Simple adsorption refrigeration system has been initially proposed of a single adsorbent bed alternately connected to a condenser and an evaporator. Theoretically, the corresponding cycle consists of two isosters and two isobars, as illustrated in the Clapeyron diagram (Fig. 1).

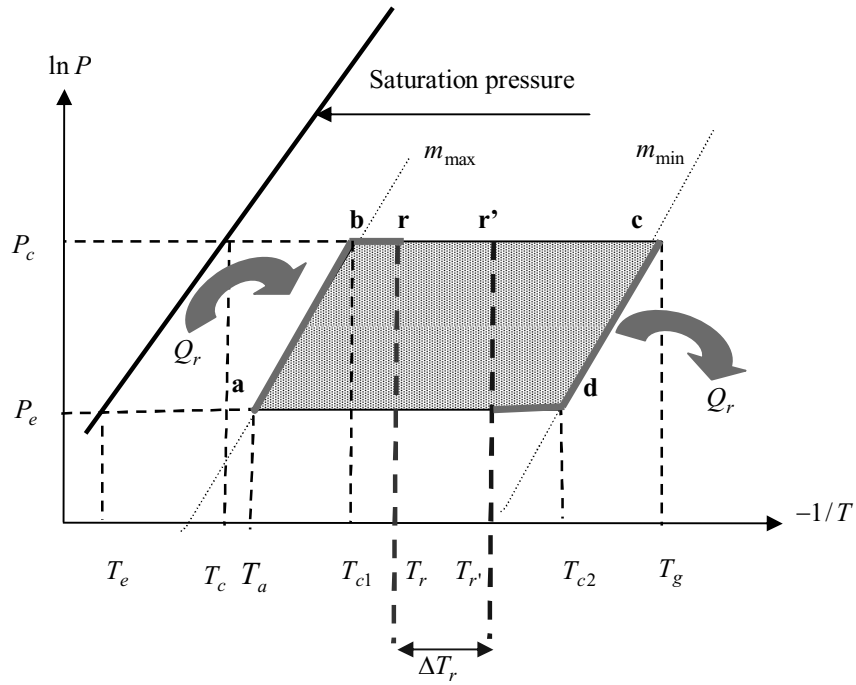

Fig. 1. Clapeyron diagram of an ideal adsorption cycle

The process starts at point a, where the adsorbent is at a low temperature T_a and at low pressure P_e (evaporation pressure). While the adsorbent is heated, the temperature and the pressure increase along the isoster which the mass of the adsorbate in the adsorbent remains constant at m_{max}. The adsorber still isolated until the pressure reaches the condenser pressure at point b (the limit point of desorption T_{c1}). At this time, the adsorber is connected with the condenser and the progressive heating of the adsorbent from point b to c causes a desorption of methanol and its vapour is condensed in the condenser and collected in a receiver. When the adsorbent reached its maximum temperature value T_g (regenerating temperature) and the adsorbed mass decreases to its minimum value m_{min} (point c), the adsorbent starts cooling along the isoster at a constant mass m_{min} to point d (the limit point of adsorption T_{c2}). During this isosteric cooling phase, the adsorbent pressure decrease until it reaches the evaporator pressure Pe. After that, the adsorber is connected to the evaporator, and both adsorption and evaporation occur while the adsorbent is cooled from point d to a. In this phase, the adsorbed mass increases up to its maximum m_{max} at point a and the adsorbent is cooled until the adsorption temperature T_a. During this phase also, the cold is produced.

In the case of the regenerative cycle, two identical, isothermal adsorbers are used and operated the same cycle but in counter phase, so that the heat recovery is obtained by transferring the heat from one adsorber (Q_r) to the other, until a fixed difference of temperature ΔT_r between beds is reached, providing continuous useful energy production.

3. Thermodynamic model

The model proposed here starts with single-bed basic cycle and is then developed for a two –bed regenerative adsorption cycle. It is a static model, it based on the use of the state equations of (adsorbent/adsorbate and liquid /vapour) at the equilibrium thermodynamic, it doesn't take account nor

the effects of the kinetics of adsorption, nor of the differences of temperature or pressure due to the heat and mass transfers and that condensation and evaporation are carried out at constant temperature. We also neglect, the effect of the thermal losses associated to the heating of the adsorber and we admit the assumption of incompressibility of the liquids and the solids during the isosteric heating and cooling phases.

To calculate the concentration of the adsorbed phase *m* as a function of the temperature *T* and the pressure P, we used the Dubinin-Astakhov equation:

$$m = w_0\, \rho_l(T) \exp\left[- D\left(T \ln \frac{P_s(T)}{P} \right)^n \right] \tag{1}$$

The maximum adsorption capacity w_0 is an indicator for the degree of activation of the used carbon. About the dependence of the temperature in the specific mass of the adsorbate, generally it was assumed to be the same of the liquid phase [15]; the exponent n lies in the range 1-3; its value depends on the type of adsorbent [16]. The value n=2 leads to the Dubinin - Radushkevich equation for a relatively homogeneous adsorbent.

The energy liberated during adsorption is called isosteric heat of adsorption and its intensity depends on the nature of the adsorbent/adsorbate pair, the amount adsorbed mass and the latent heat, which is given as [17]:

$$q_{st} = L(T) + R\,T\, \ln\left(\frac{P_s(T)}{P} \right) + \left[\frac{\alpha\, R\, T}{n\, D} \right] \left[T \ln \frac{p_s}{P} \right]^{(1-n)} \tag{2}$$

Where, α is the coefficient of thermal expansion of the liquid adsorbate.

The definition of the thermodynamic cycle is completed when the two limit points of this cycle are given and defined. To obtain the analytical relations between T_{c1}, T_{c2} with the evaporation and condensation temperature, we used the isosterity condition during the two isoster periods (a-b) and (c-d) (see fig. 1):

$$m(T_a, P_e) = m(T_{c1}, P_c) \tag{3}$$

$$m(T_g, P_c) = m(T_{c2}, P_e) \tag{4}$$

And, by the application of the equation (1) into equation (3) and equation (4) we obtain:

$$\rho_l(T_a) \exp\left[- D\left(T_a \ln \frac{P_s(T_a)}{P_e} \right)^n \right] = \rho_l(T_{c1}) \exp\left[- D\left(T_{c1} \ln \frac{P_s(T_{c1})}{P_c} \right)^n \right] \tag{5}$$

$$\rho_l(T_g) \exp\left[- D\left(T_g \ln \frac{P_s(T_g)}{P_c} \right)^n \right] = \rho_l(T_{c2}) \exp\left[- D\left(T_{c2} \ln \frac{P_s(T_{c2})}{P_e} \right)^n \right] \tag{6}$$

The solution of the equations (5) and (6) gives the values of the two the limit temperatures of the cycle.
In order to calculate the coefficient of performance of the machine, all the thermal contributions must be calculated in detail; the most important equations used in the model are described below.
The heat that must be supplied to the adsorber for its heating is:

$$Q_c = Q_{ab} + Q_{bc} \tag{7}$$

Where, Q_{ab} is the heat that must be supplied to the adsorber for its isosteric heating, it consists the sensible heat of the adsorbent, the adsorber and the adsorbate:

$$Q_{ab} = \int_{T_a}^{T_{c1}} m_a \left[Cp_a + m_g Cp_g + m_{\max} Cp_{ml}(T) \right] dT \tag{8}$$

Q_{bc} is the heat needed for the desorption phase, it consists the sensible heat of the adsorbent, the adsorber, the adsorbate and the heat of desorption:

$$Q_{bc} = \int_{T_{c1}}^{T_g} m_a \left[Cp_a + m_g Cp_g + m(T) Cp_{ml}(T) \right] dT + Q_{des} \tag{9}$$

The heat of desorption can be calculated as:

$$\mathrm{Q_{des}} = -m_a \int_{\mathrm{m_{max}}}^{\mathrm{m_{min}}} q_{st}\, dm \tag{10}$$

Where, q_{st} is a function of the adsorbed mass, it have a positive sign during the desorption phase. The differentiation of the adsorbed mass of the equation (1) gives:

$$d\,m = n\,D\,m\,T^n \left(\ln \frac{p_s(T)}{p} \right)^{n-1} \left[d \ln P - \frac{q_{st}}{R\,T^2} d\,T \right] \tag{11}$$

During the desorption phase, the pressure is constant and equals to the condensation pressure. Thus, Q_{des} becomes:

$$\mathrm{Q_{des}} = m_a\, n\, D \int_{T_{c1}}^{Tg} m(T)\; T^n \left(\ln \frac{P_s(T)}{P_c} \right)^{n-1} \frac{{q_{st}}^2}{RT^2}\, dT \tag{12}$$

Where, the two terms q_{st} and $m(T)$ are evaluated at the condensation pressure. Thus Q_{bc} becomes:

$$Q_{bc} = \int_{T_{c1}}^{T_g} m_a \left[Cp_a + m_g Cp_g + m(T) Cp_{ml}(T) + n\,D\,m(T)\; T^n \left(\ln \frac{P_s(T)}{P_c} \right)^{n-1} \frac{{q_{st}}^2}{RT^2} \right] dT \tag{13}$$

During the isosteric cooling phase, only the sensible heat of the adsorbent, the adsorber, the adsorbate is withdrawn from the bed:

$$Q_{cd} = \int_{T_{c2}}^{T_g} m_a \left[Cp_a + m_g Cp_g + m_{\min} Cp_{ml}(T) \right] dT \tag{14}$$

While during the adsorption phase, the energy released is equal to the heat of adsorption, plus the sensible heat obtained from cooling of adsorbent, adsorber and adsorbate, from critical adsorption temperature to adsorption temperature, minus the energy needed to heat up the vapour from evaporation to adsorption temperature, it is given by:

$$Q_{da} = m_a \int_{T_a}^{T_{c2}} \left[Cp_a + m_g Cp_g + m(T) Cp_{ml}(T) \right] dT + m_a \int_{m_{\min}}^{m_{\max}} \left[q_{st} - (T - T_e) Cp_{mg}(T)\, dm \right] \tag{15}$$

During the adsorption phase, the pressure is constant and equals to the evaporation pressure; the differentiation of the adsorbed mass (equation 11); two terms q_{st} and $m(T)$ in equation (15) are evaluated at the evaporation pressure. Thus Q_{da} becomes:

$$Q_{da} = m_a \int_{T_a}^{T_{c2}} \left[Cp_a + m_g Cp_g + m(T) Cp_{ml}(T) + q_{st} \frac{\partial m}{\partial T} - (T - T_e) Cp_{mg}(T) \frac{\partial m}{\partial T} \right] dT \tag{16}$$

The energy that must be supplied to the evaporator Q_f, is calculated as the latent heat of evaporation of the cycled adsorbate, minus the sensible heat of the adsorbate that entering the evaporator at condensation temperature:

$$Q_f = m_a (m_{\max} - m_{\min}) \left[L(T_e) - \int_{T_e}^{T_c} Cp_{ml}(T)\, dT \right] \tag{17}$$

On the basis of the previous equations, the coefficient of performance of single adsorbent bed can be calculated as the ratio of useful effect produced and energy supplied to the machine:

$$COP_s = \frac{Q_f}{Q_c} = \frac{Q_f}{Q_{ab} + Q_{bc}} \tag{18}$$

In the following, the developed model is described with reference to a single bed adsorption system and the main difference introduced in modeling of a two bed system are also presented.

In the regenerative cycle the above parameters have been calculated between $m_{\max}$ and a generic isosteric line $m_r \geq m_{min}$. The energy incoming to the system when its temperature increase from T_a to a generic temperature T_r represents the function Q_{ar}. This energy can be represented by the following expression for $T_{c1} < T_r < T_{c2}$:

$$Q_{ar} = Q_{ab} + \int_{T_{c1}}^{T_r} m_a \left[Cp_a + m_g Cp_g + m(T) Cp_{ml}(T) + q_{st} \frac{\partial m}{\partial T} \right] dT \tag{19}$$

In the same way, the energy out coming from the system when its temperature decrease from T_g to a generic value $T_{r'}$ represents the function $Q_{cr'}$; where $T_{r'}=T_r+\Delta T_r$ and ΔT_r is the two adsorber temperature difference at end of heat recovery.
The function $Q_{cr'}$ can be represented by the following expression:

$$Q_{cr'} = Q_{cd} + m_a \int_{T_{c2}}^{T_{r'}} \left[Cp_a + m_g Cp_g + m(T) Cp_{ml}(T) + q_{st} \frac{\partial m}{\partial T} - (T - T_e) Cp_{mg}(T) \frac{\partial m}{\partial T} \right] dT \tag{20}$$

The temperature at which Q_{ar} is equal to the absolute value of $Q_{cr'}$ is the final temperature of the regenerative phase T_r and the corresponding value of the function Q_{ar} or $Q_{cr'}$ is the regenerative energy Q_r:

$$\begin{aligned} Q_r &= Q_{ab} + \int_{T_{c1}}^{T_r} m_a \left[Cp_a + m_g Cp_g + m(T) Cp_{ml}(T) + q_{st} \frac{\partial m}{\partial T} \right] dT \\ &= Q_{cd} + m_a \int_{T_{c2}}^{T_{r'}} \left[Cp_a + m_g Cp_g + m(T) Cp_{ml}(T) + q_{st} \frac{\partial m}{\partial T} - (T - T_e) Cp_{mg}(T) \frac{\partial m}{\partial T} \right] dT \end{aligned} \tag{21}$$

In this case, the performance of the machine can be calculated by the following formulae:

$$COP_d = \frac{COP_s}{1 - r} \tag{22}$$

Where, r is the coefficient of regeneration, it can be calculated by:

$$r = \frac{Q_r}{Q_{ab} + Q_{bc}} \tag{23}$$

4. Results

We admit the following data: the pair activated carbon AC-35/methanol as an adsorptive pair, this last has proved to be the best pair among those studied so far; w_0=0.425 l /kg, n=2.15 and D=5.02.10^{-7} as the parameters of the (D-A) equation [18]; the copper is a material of construction of the adsorber; m_g=5 kg its mass and m_a=1 kg is an adsorbent mass. The specific heat of the adsorbent and of the adsorber are, respectively: Cp_a=920 KJ/kg K and Cp_g=380 KJ/kg K. The estimates of the saturation pressure, the specific heat and the latent heat of the methanol are given by R. C. Weast [19] and A. Bejan, A. D. Kraus [20]. Two-adsorber temperature difference at the end of heat recovery ΔT_r = 2 °C, adsorption temperature T_a =25°C, condensation temperature T_c =30°C, evaporation temperature T_e =0°C and regenerating

temperature T_g =105 °C in the case of single bed adsorbent; T_g =125 °C in the case of double bed adsorbent.

4.1. Limit points of desorption and adsorption of the cycle

The Fig. 2 shows that the limit temperature of desorption T_{c1} is a decreasing function of evaporation temperature T_e and an increasing function of condensation temperature T_c.

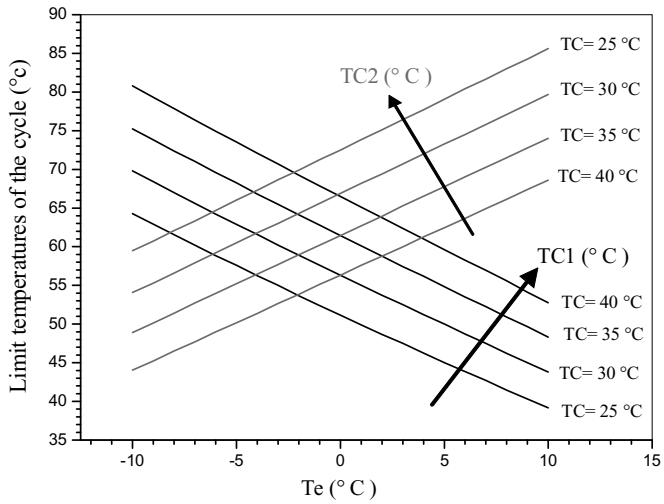

Fig. 2. The effect of evaporation and condensation temperature on the limit points of the cycle

Indeed, the reduction of the evaporation temperature drives to a reduction of the saturation pressure at this temperature and consequently, a reduction in the adsorbed mass $m_{max}=m(T_a,P_e)$. Therefore, it is necessary to increase the adsorber temperature to reach the condenser pressure, so that the first drop of liquid appears in the condenser. A reduction of the condensation temperature T_c drives to a reduction of saturation pressure in the condenser. This implies that, it is necessary to decrease the adsorber temperature to reach the condenser pressure, so that the desorption starts. Therefore, the limit temperature of desorption T_{c1} decreases. The inverse effect is happening to the limit temperature of adsorption T_{c2}.

4.2. Effect of regenerating temperature

Let us recall that the regenerating temperature of the cycle T_g is defined as the maximum temperature reached by the adsorbent at the end of the phase of desorption-condensation. Thus, the range of the variation of T_g is much larger than the other operating temperatures of the cycle. Therefore, this temperature has the most significant effect on the performance of the system.

The influence of the regenerating temperature on performance coefficients, temperature at the end of heat recovery and both of recovery ratio and regenerative heat is shown in Figs. 3, 4 and 5, respectively.

From the Fig. 3, we see that both of COP_s and COP_d increases with T_g until a maximum reached for an optimal temperature noted T_{gmax} equal to 105 °C for simple cycle and 125 °C for regenerative cycle. For the temperatures superior to these values the performances decrease. This behaviour can be justifies by the fact that after a certain regenerating temperature T_{gmax}, the energy of heating only serves to increase the activated carbon temperature, the temperature of the metal parts of the adsorber and the methanol

temperature, nevertheless the desorbed mass of the methanol m_{min} becomes more and more weak. Where, the heat provided to the adsorber increases more than the quantity of cold produced at evaporator level.

It is clear that, in the case of two adsorbers, the performance of the system increases in an appreciable manner compared to the case of one adsorber. On the basic of the previous consideration regarding the optimum regenerating temperatures, the performances are predicted as: COP_s =0.483, COP_d =0.675 and the heat recovery ration is r=0.3 (r= 30 %).

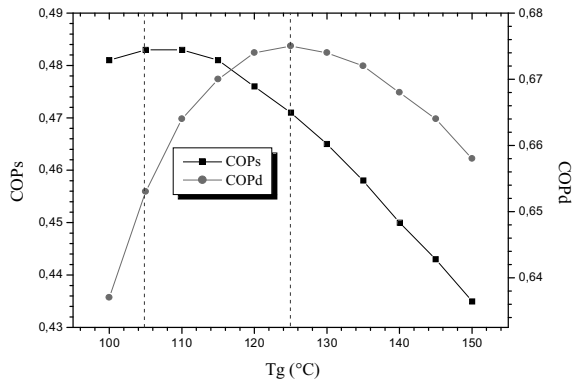

Fig. 3. Influence of regenerating temperature T_g on performance coefficients COP_s and COP_d.

The Fig. 4 shows the evolution of the temperature at the end of the heat recovery T_r as a function of the regenerating temperature T_g. Increasing T_g indicates a significant increase of T_r, therefore an increase of the internal regenerative heat Q_r and heat recovery ratio r defined by the equation (23) (see Fig.5).

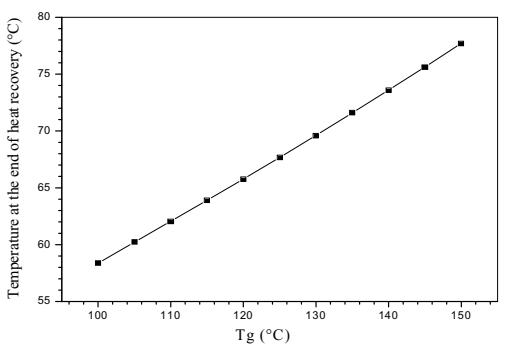

Fig. 4. Influence of regenerating temperature T_g on temperature at the end of heat recovery T_r.

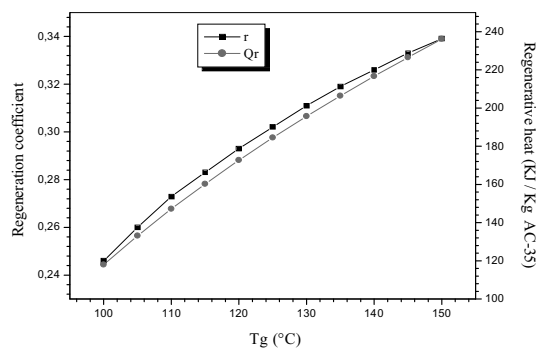

Fig. 5. Influence of regenerating temperature T_g on heat recovery ratio r and regenerative heat Q_r.

The regenerating temperature T_g is a design variable that must be optimized. Generally, it is stipulated to obtain a large amount of cycled masses at lower levels. In the case of the adsorption of the methanol in the activated carbon AC-35, this temperature is limited by 150 °C, because the methanol would

decompose, the process of adsorption is blocked and the adsorption power of activated carbon decreases sharply beyond above mentioned temperature [14].

In solar refrigerating machines with adsorption, T_g depends on the meteorology given by the solar radiation available and on the solar collector properties [16, 21]. The use of a good selective layer or a system with concentration of the solar radiation also goes in the sense to increase T_g [16].

4.3. Effect of two-adsorber temperature difference at the end of heat recovery

Fig. 6 shows the variation of the performance coefficient of the regenerative cycle with the two-adsorber temperature difference at the end of heat recovery ΔT_r (varying between 0 and 10°C). The figure represents the logical decrease of COP_d with an increase of ΔT_r. Where the heat transfer between two adsorbers becomes largest when $\Delta T_r=0$ °C and decreases with the increase of ΔT_r (Fig.7). Thus, T_r decreases (Fig. 8) and like the regeneration coefficient is defined as the fraction between the heat recovered between two adsorbers and the heat required in a process without heat regeneration, this coefficient decreases also (Fig.7).

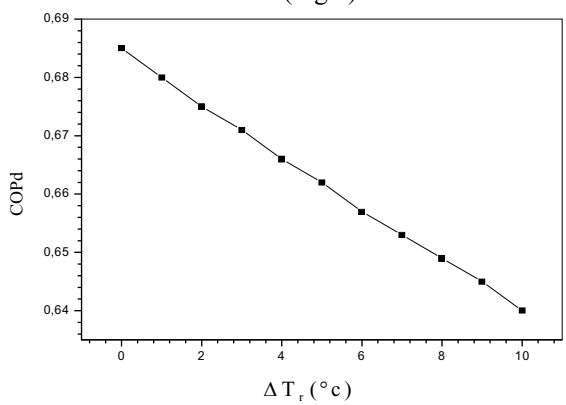

Fig. 6. Influence of the two-adsorber temperature difference at end of heat recovery on performance coefficient COP_d.

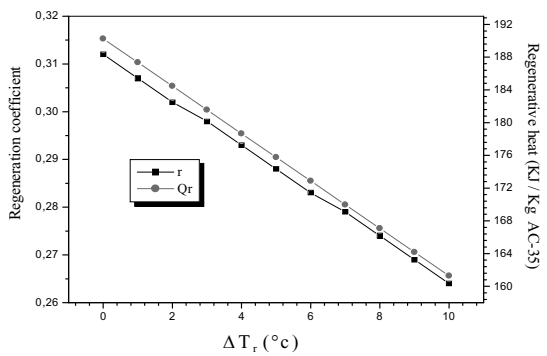

Fig. 7. Influence of the two-adsorber temperature difference at end of heat recovery on heat recovery ratio *r*and regenerative heat Q_r.

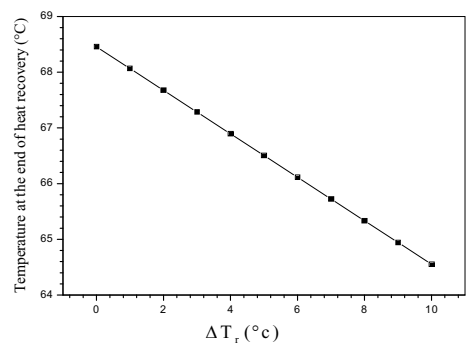

Fig. 8. Influence of the two-adsorber temperature difference at end of heat recovery on temperature at the end of heat recovery T_r.

4.4. Effect of the mass of the metal parts of the adsorber

We present in the Fig. 9 the effect of the mass of the metal parts of the adsorber on the performance coefficients COP_s and COP_d, by varying the mass m_g. According to this figure, the adsorber metal mass increases, COP_s and COP_d reduce. The reason is that the bigger the heat capacity of the adsorber materials is, the more the heat will be consumed. Thus, a part of heating power becomes energy loss due to the switch between two adsorbers. This kind of energy loss leads to the decrease of performance coefficients of system COP_s and COP_d.On contrary, the heat recovery ratio r, the heat recovered Q_r and the temperature at the end of heat recovery T_r, are on the increase for the same reasons.(Figs. 10 and 11).

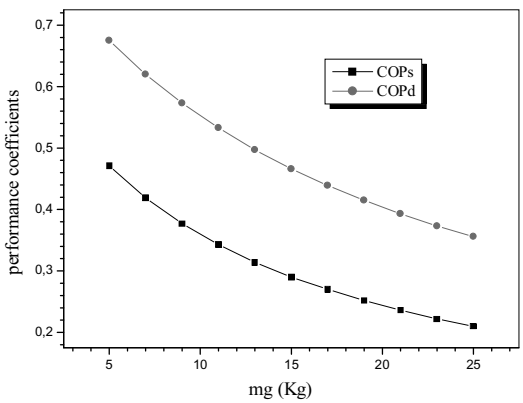

Fig. 9. Influence of adsorber mass m_g on performance coefficients COP_s and COP_d.

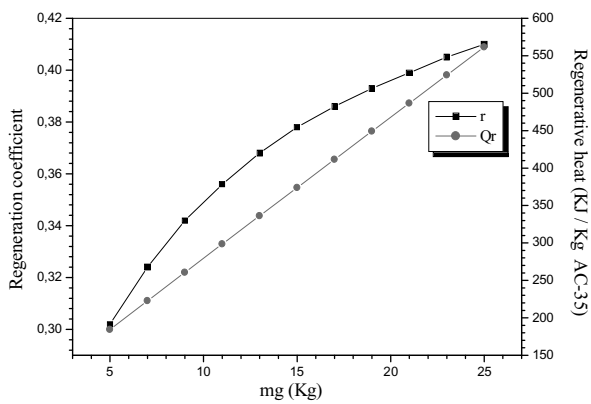

Fig. 10. Influence of adsorber mass m_g on heat recovery ratio r and regenerative heat Q_r.

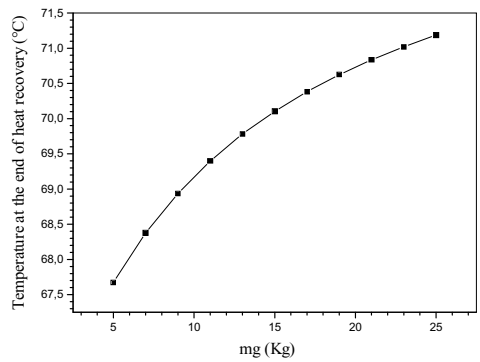

Fig. 11. Influence of adsorber mass m_g on temperature at the end of heat recovery T_r.

Moreover, we can say that the adsorber materials which have the low specific heats lead to good performances. However, it is necessary that these materials are compatible with the used adsorbate. As an example, although copper gives good performances, nevertheless we can't use it with ammonia as an

adsorbate. We conclude that the selection criterion of construction material of the adsorber and the mass of his metal parts must base on two conditions: It is necessary that the material is compatible with the used adsorbate and that the heat capacity of the metal parts of the adsorber is lowest than possible.

4.5. Effect of evaporation temperature

The influence of evaporation temperature on the performance coefficients COP_s and COP_d has been evaluated and the Fig.12 shows its behaviour. Indeed, The two coefficients increase with the evaporation temperature T_e. This increment in evaporation temperature implies that the saturation pressure $P_s(T_e)$ increases together with the adsorbed mass of methanol m_{max}. Therefore, it increases the cycled mass of the methanol. The cooling power increases and also, the COP_s. Moreover, an increase in T_e drives to an increase in the regenerative heat Q_r and consequently in the heat recovery ratio r (Fig.13) and consequently the COP_d (Fig.12).

Generally, T_e depends on the application goal [4], i.e. for the ice making it is better to limit it between -5 °C and -10 °C and for air conditioning and vaccination storage T_e can be increased to around 5 °C and 8 °C, respectively.

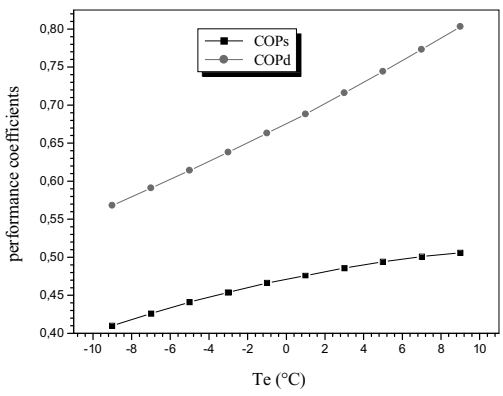

Fig. 12. The effect of evaporation temperature on performance coefficients COP_s and COP_d.

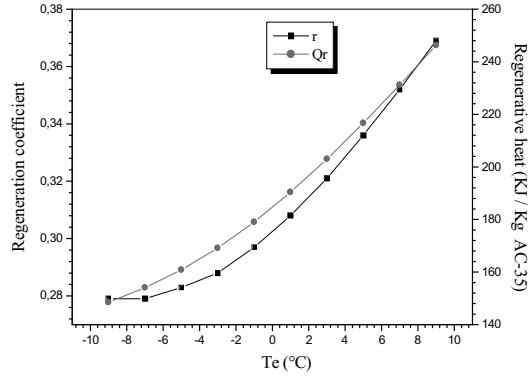

Fig. 13. The effect of evaporation temperature on heat recovery ratio r and regenerative heat Q_r.

4.6. Effect of condensation temperature

The Figs. 14 and 15 show how the condensation temperature effects the performance coefficients COP_s and COP_d and the heat recovery ratio r and regenerative heat Q_r, respectively.

The COP_s of the system decreases with the increase of condensation temperature. Because of an increase in condensation temperature makes the saturation pressure $P_s(T_c)$ increases. Thus, the adsorbed mass of the methanol m_{min} increases. Consequently, there is a decreasing in the cycled mass of the methanol, the cooling power and also, in the COP_s. Moreover, an increase in T_c drives to an decrease in the regenerative heat Q_r and consequently in the heat recovery ratio r (Fig.15) and COP_d (Fig. 14).

In the case of a solar adsorption refrigerating machine, it is difficult to fix certain conditions, such as the temperature of the condenser. This last depends on several random factors related to the type of the

site application climate and this is right for an air condenser that for a water-cooled condenser [16]. Thus, T_c for an air condenser can't be lower than the ambient temperature.

A similar effect observed for condensation temperature is noted for adsorption temperature. Thus, we always interest to begin the cycle corresponding to a solar refrigerating machine in adsorption with the lowest possible temperature, so that the maximum adsorbed mass m_{max} is as high as possible, this maximizes the cycled mass and performance coefficients COP_s and COP_d.

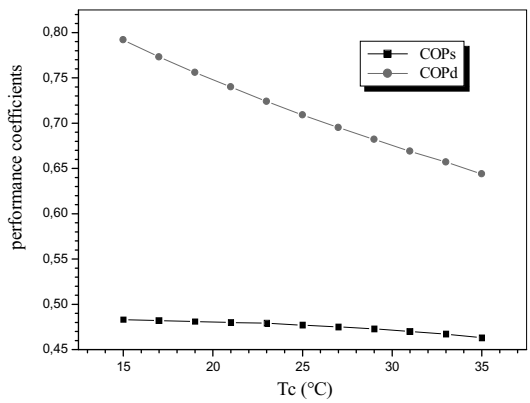

Fig. 14 . The effect of condensation temperature on performance coefficients COP_s and COP_d.

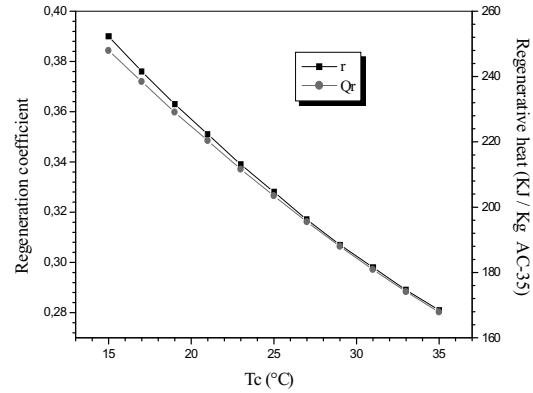

Fig. 15. The effect of condensation temperature on heat recovery ratio r and regenerative heat Q_r.

5. Conclusion

A detailed thermodynamic model has been developed for the analysis of solid adsorption refrigeration system (single and two adsorbers), using the pair activated carbon AC-35/ methanol as an adsorptive pair. This model was usually expressed in algebraic or relatively simple equations based on the representation of Dubinin-Astakhov. The developed model is described with reference to a single bed adsorption system and the main differences introduced in modelling of a two bed system are also presented.

Based on the previous results and analysis discussed above, some conclusions are summarized in the following:

- This model is a good tool for optimizing the adsorption system(single and two adsorbers);
- The determination of two limit points of desorption or adsorption is necessary in a thermodynamic study of this type of systems at different operating conditions;
- The performance coefficients, heat recovery ratio and regenerative heat depend strongly on the operating temperatures (condensation and evaporation temperature);
- There is an optimum regenerating temperature for the pair activated carbon AC-35/methanol at various condensation and evaporation temperatures in the case of single and two adsorbers ;
- The characteristics of the adsorber (its metallic mass) have an important effect to improve the performance of the system;
- The two-adsorber temperature difference at the end of heat recovery has a strong effect on the performances of the system;

- The performance coefficient of double bed adsorption refrigeration cycle is better than that of single bed;
- The simulation results give a rough description for the complex relationships of parameters in adsorption simple and heat recovery systems. It is useful for the design of such systems.

With a study such as this, it is possible to estimate the performance of an adsorption refrigerating cycle, which can be easily transported to any type of adsorbate and several types of adsorbent, especially activated carbons. This method can also be applied to all the different cycles such as cascading cycle, mass recovery …etc.

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